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WP 3.1: Land Productivity

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Assessment of potential use of climatic forecasts and Trends in crop and rangeland (vegetation) productivity predicted for climate change scenarios

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1. Introduction

In West-Africa countries, most economies and people depend on rainfed agriculture. In this area, rainfall is highly variable and, from the period 1931-1960 to 1968-1990, the annual rainfall has decreased 15 to 40% (Nicholson, 2000). Since the mid 1990's, an increase in rainfall is detected, but only to reach the level of 1970's rainfall (Mahé and Paturel, 2009). In addition, most studies considering climate change scenarios show a negative impact of future climate on crop yield (Challinor et al., 2005; Dingkuhn et al., 2006; Lobell and Field, 2007; Porter and Semenov, 2005), even if they do not agree on the amplitude of this impact.

In this study, we present first results of crop yields simulations carried out for present-day and for future climate, using RCMs output from ENSEMBLES European project.

This study is organized as follows: Section 2 delineates the area selected for study and presents the meteorological data. Section 3 presents results for both present-day and future climates. Section 4 presents conclusion.

2. Materials and Methods

In this section, study area is succinctly presented, with synoptic stations selected. Different datasets are described, for present-day and future. The crop model used in this study is introduced as well as yields simulations protocol.

2.1 Study area and climate data

Analyses of crop yields simulations in present-day and future climates are carried out in Senegal, for 12 synoptic stations (Figure 1~~Figure 1~~). This country is located in West Africa, in sahelian band (10N-20N). The main region of cereals cultivation is located between 14N and 16N.

The rainfall dataset is from 12 synoptic stations that are located through country, from north to south and from east to west. These stations provide some climate data, used by crop model presented in section 2.3, at time-scale: precipitation (P), mean relative humidity (HR), minimum (TN) and maximum temperature (TX), 2-m wind speed (W2), sunshine duration (IN) and downward short-wave radiation (Rs). The limited numbers of stations is due to the choice of using all climate parameters available at stations, and not only precipitation, for which more stations are available.

Climate data, except rainfall, are used to compute reference crop evapotranspiration (ETo), from Penman-Monteith formula (Allen et al., 1998). ETo represents the evapotranspiration from a standardized vegetated surface. Evapotranspiration is the major source of water loss during plant growth, and is affected by weather conditions. High water loss occurs during windy day, with clear sky, low humidity and high temperatures.

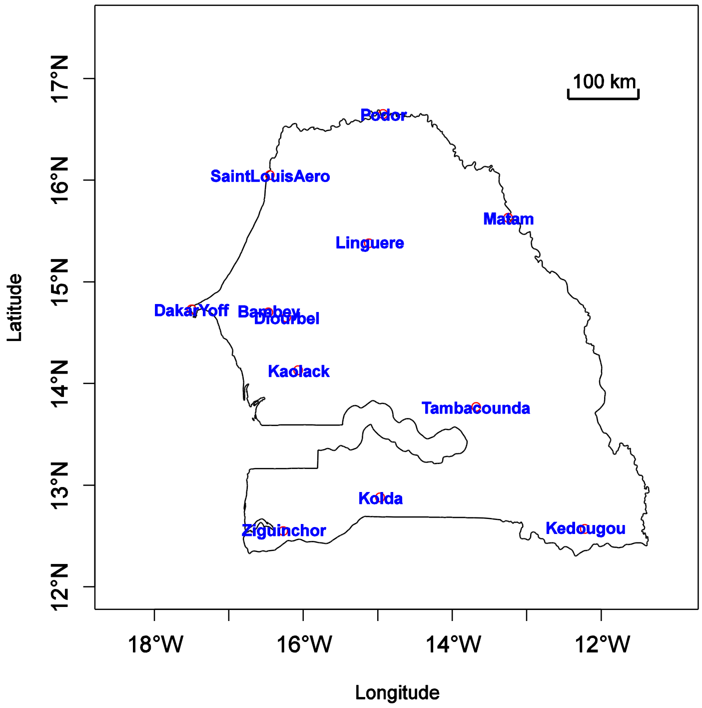


Figure 1: Senegalese synoptic stations location

2.2 ENSEMBLES datasets

The project's principal objective is to allow the uncertainty in climate projections to be measured, so that a clearer picture of future climate can be formed (van der Linden, 2009). One of the specific aims is to use the results by linking outputs of the ensemble prediction system to a range of applications, including agriculture. The project is constructed around ten Research Themes (RTs). Two of these RTs, RT3 and RT2B, are used in the present study. RT3 had the responsibility for providing improved climate model tools developed in the context of regional climate models (RCMs), at spatial scales of 50km at AMMA-region (Christensen et al., 2009). RT3 provides 15-year experiments over West Africa driven by the ERA-INTERIM reanalysis of the ECMWF. Among available runs, 5 was chosen to study (i) the ability of them to reproduce the climate data at station scale, (ii) the crop yields when crop model is forced by RCMs output. These runs are from Danmarks Meteorologiske Institut (DMI) with HIRHAM output; Koninklijk Nederlands Meteorologisch Instituut (KNMI) with RACMO output; Meteorologisk institutt (METNO) with HIRHAM output; Sveriges Meteorologiska och Hydrologiska Institut (SMHI) with RCA output; Universidad de Castilla – La Mancha (UCLM) with PROMES output.

The main task for RT2B was to provide relevant and – if possible – robust information on regional climate change as input data for climate change impact assessments (Goodess et al., 2009). RCMs are driven by ECHAM5-r3 (DMI and KNMI) or HadCM3Q0 (METNO, SMHI and UCLM) global climate models output. The emission scenario chosen is balance across all sources (A1B).

ENSEMBLES project provide, for RT3 and RT2B, same type of climate data than synoptic stations, at daily time-scale: precipitation, relative humidity, temperatures, wind speed, sunshine duration and downward short-wave radiation.

2.3 Crop model SARRA-H

A deterministic crop model, SARRA-H (Baron et al., 2005; Dingkuhn et al., 2003; Sultan et al., 2005), is used for simulating (present-day) and forecasting (future) crop yields in Senegal. SARRA-H simulates yield attainable under water-limited conditions by simulating the soil water balance, potential and actual evapotranspiration, phenology, potential and water-limited carbon assimilation, and biomass partitioning (Dingkuhn et al., 2003). For this study, the crop model is calibrated for 2 levels of sorghum production technology: a *local* variety; which depicts farmers practices, and an *improved* variety (Dingkuhn et al., 2008; Kouressy et al., 2008a), based on experimental field data and parameterization procedures (Dingkuhn et al., 2008). The *local* is a tall, traditional, highly photoperiod-sensitive *Guinea* landrace, collected in southern Mali. The *improved* is a dwarf breeding line sharing 75% of *local*'s genome, in which the photoperiod-sensitivity has been preserved (CIRAD/IER). This variety is adapted to traditional crop calendars, seasonal rainfall variability and farmer's choice, to ameliorate potential crop yields.

These varieties were first calibrated for Mali. In order to confront our results to published studies, we use these varieties for Senegal. Crop simulations are based on daily climate data, for each station.

2.4 Crop yields simulations protocol

Two periods have been chosen for crop yields simulations. On the one hand, the period 1990-2000, to assess models output for the present-day. This period is shared by observations (period 1950-2000) and by RCMs runs (period 1990-2007). On the other hand, the period 1990-2050, to evaluate climate change impact on crop yields.

Over the period 1990-2000, two different simulations have been performed:

- A first set of crop yields simulations, with climate data observed at synoptic stations. Simulations are performed between 15th April and 30th November, for each year. During this period, sowing and harvest are observed in country. These simulations are used as control simulations, to assess quality of simulations performed with RCMs output,

- A second set of simulations, driven by RCMs output, are carried out. RCMs output are given for a 50x50km grid. In order to force crop model with them, a bilinear interpolation is used to obtain climate data at each station. For this period, RCMs are driven by ERA-INTERIM. These simulations are compared to control simulations, to assess the ability to reproduce observations and crop yields. In second time, best RCMs are used for forecasting study.

Over the period 1990-2050, one simulation has been performed. Crop model is forced by best RCMs output, driven by GCMs. This simulation is used to estimate future trends in crop yields, for the different sorghum varieties. As for present-day period, RCMs output are interpolated at each synoptic station location.

3. Results

We first test the ability of five RCMs to reproduce variability of some climatic parameters, used by crop model to simulate yields. Then, we choose the best two models, for yields forecasting for the period 1990-2050.

3.1 Assessment of potential use of climate models

Before using RT3 climate data for crop yields simulation, their ability to well reproduce observed climate data at country and station space-scales is tested. For each station, RCMs output are compared to observed data, for the period 1990-2000, between 15th April and 30th November. At country scales, we only use 12 stations to calculate means, because only these stations give observed climate parameters, used by crop model. Results are shown for some important climatic parameters for crop yields: precipitations, temperatures, potential evapotranspiration.

SARRA-H crop model is driven by precipitation, because of water-limited conditions. At country scale, the Taylor diagram (Figure 2~~Figure 2~~) shows that, compared to observed rainfall standard deviation (4.5mm/day, black line), rainfall simulated by two models (DMI/HIRHAM, violet point and METNO/HIRHAM, blue point) have almost the same variability (respectively 4.7 and 4.3mm/day).

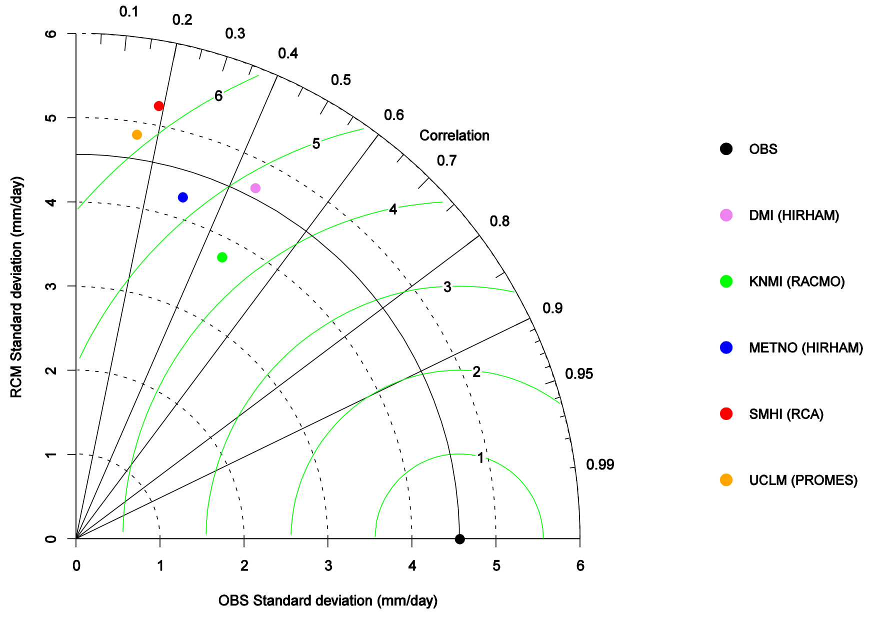


Figure 2: Taylor diagram, comparing RCMs output (colors) and observations (black) for precipitation at country space-scale, from 15th April to 30th November, during 1990-2000

But rainfalls of one RCM (KNMI/RACMO, green point) have little variability compared to observed values (3.8mm/day). Two RCMs (UCLM/PROMES, orange point and SMHI/RCA, red point) simulate rainfalls with higher variability (respectively 4.9 and 5.2mm/day). All RCMs show large centered root mean square errors (RMSE, green curve lines) in precipitation fields by all RCMs. RMSE values (green lines) are from 4.5 mm/day to more than 6 mm/day.

The Taylor diagram shows also low correlations with observations, between 0.1 and 0.45. It denotes that RCMs are not able to well reproduce high precipitations. Figure 3~~Figure 3~~ compares distribution of rainfall inside rainy seasons (period 1990-2000) at country scale, for observations and different RCM output. Distributions for RCMs show distortions, compared to distribution for observation. Theses distortions are due to (i) underestimation of the frequency of rainless days (f), (ii) overestimation of the occurrence of low and intermediate rainfall (until 15mm for three models, 20 mm for KNMI/RACMO, and 25mm for DMI/HIRHAM), (iii) underestimation of high precipitations. Generally, RCM simulate more rainy days than in reality, to obtain coherent seasonal amounts, compared to observations.

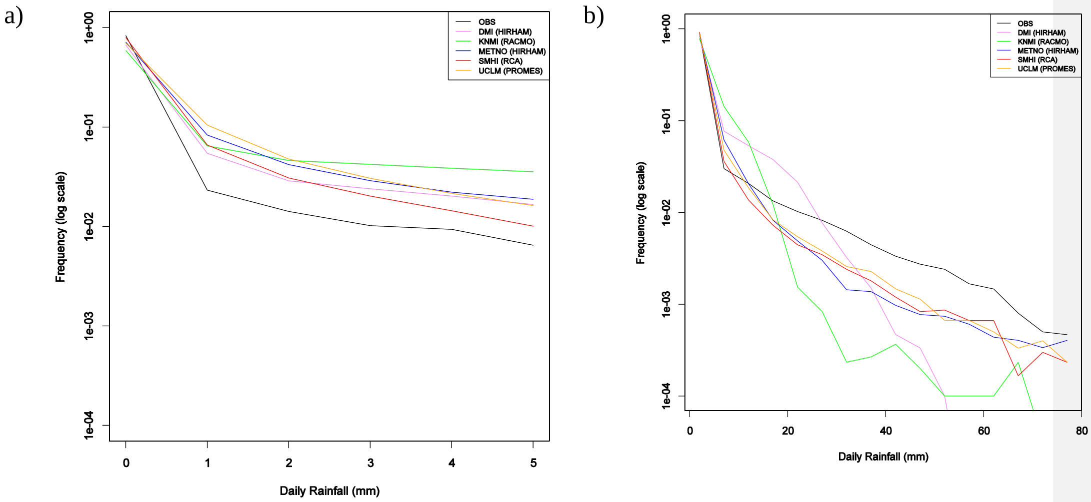


Figure 3: Daily rainfall distribution from 15th April to 30th November during 1990-2000 for (a) low values precipitation (from 0 to 5 mm/day) and (b) for intermediate and high values of precipitations.

Sorghum is sensitive to high temperatures stress during reproductive development. If maximum temperatures in RCM are higher than mortality threshold, there won't be simulated harvest. At country scale, maximum 2-m temperatures of four RCMs have high variability (Figure 4~~Figure 4~~a) between 3.4 and 5.4°C, above observed standard deviation (2.3°C).

This high variability is due to underestimation of occurrences of lowest temperatures in the south of the country (Figure 4~~Figure 4~~b), and a slight overestimation in the central part of Senegal. Values of centered RMSE, showing an error in simulations of temperatures by models, are high. If one model (DMI/HIRAM) has RMSE close to 2°C, three models show values about 2.5°C. And UCLM/PROMES model tends to overestimate occurrence of high temperatures in almost all stations, except Dakar-Yoff (west of country). This systematic overestimation explains bad RMSE value (4.4°C). The diagram shows relatively high correlations (between 0.6 and 0.8) between observations and simulations, at country scale. In both observations and simulations, temperatures increase (decrease) together.

a)

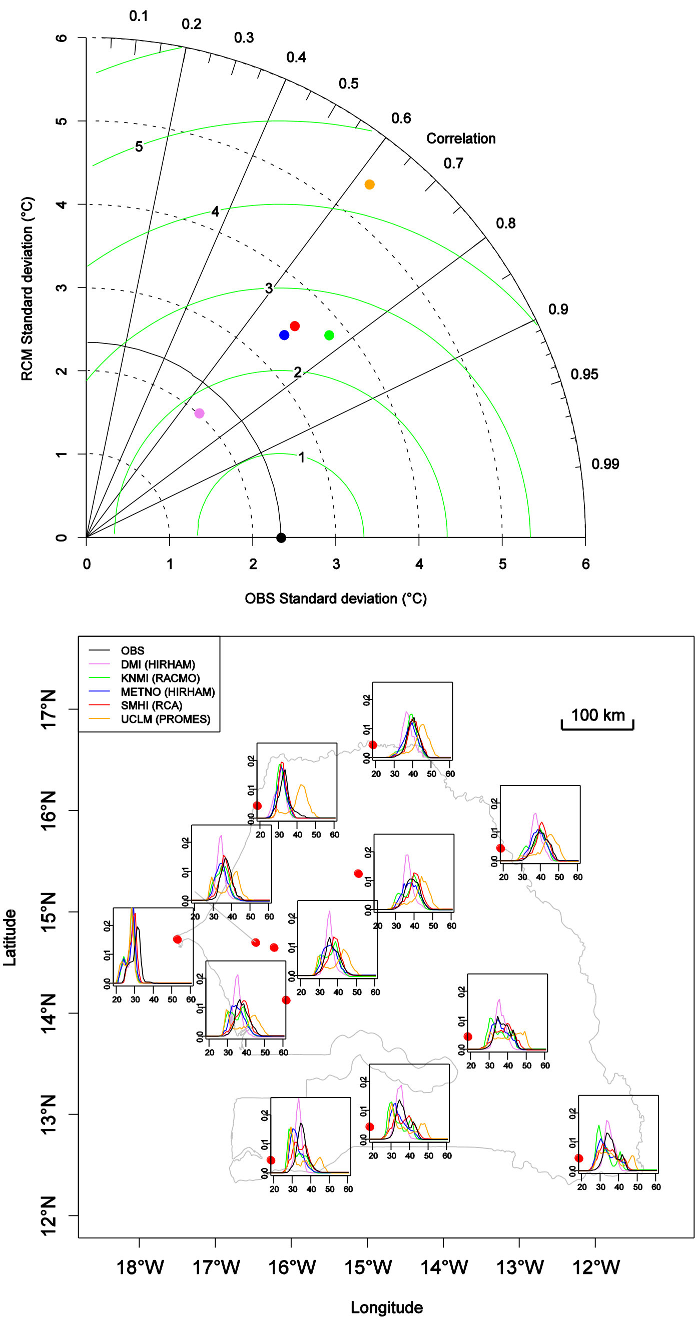
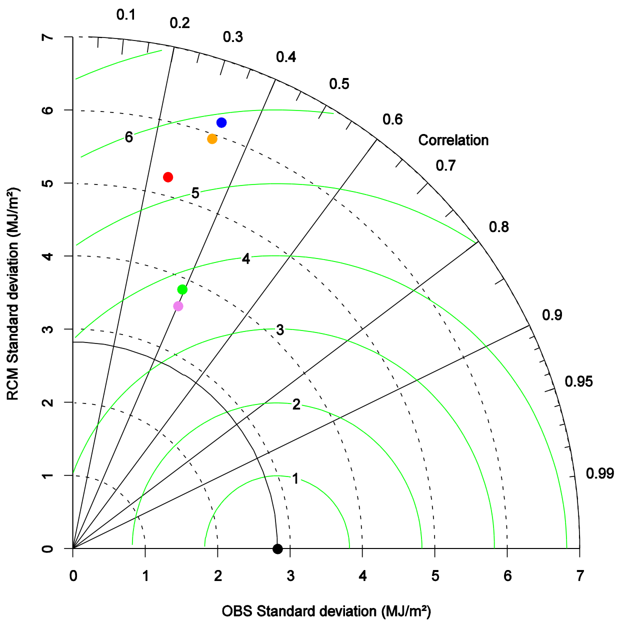


Figure 4: (a) Taylor diagram, comparing RCMs output (colors) and observations (black) for maximum 2-m temperatures at country space-scale, from 15th April to 30th November, during 1990-2000, (b) daily maximum 2-m temperatures distribution for the same period, for observations and models.

a)



b)

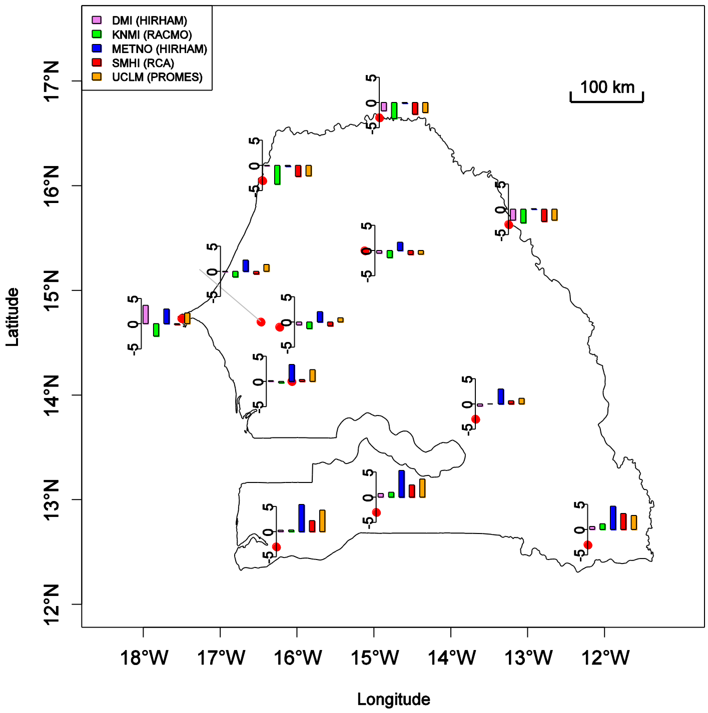


Figure 5: (a) Taylor diagram, comparing RCMs output (colors) and observations (black) for solar radiation at country space-scale, from 15th April to 30th November, during 1990-2000, (b) biases calculated for solar radiation for the same period for each model

Solar radiation the source of energy caught up by plants to product biomass. The ability of RCMs to well reproduce downward solar radiation at country scale is weak (Figure 5~~Figure 5~~a). Diagram shows two groups: a group with better, but weak, correlations (0.4) and relatively high RMSE (between 3.5 and 4 MJ/m^2), with DMI/HIRHAM and KNMI/RACMO models. Another group aggregating the other models: METNO, SMHI and UCLM, with lower correlations and higher RMSE values (upper than 5 MJ/m^2). All models have high standard deviation, compared to reference (2.9 MJ/m^2): from 3.5 to 6 MJ.m^2. At stations scale, there is a south-north gradient bias (Figure 5~~Figure 5~~b). In general, considering all RCMs, biases are positive in the south and negative in the north of the country. So, models underestimate (overestimate) solar radiation in the south (north). Two models show good results (DMI/HIRHAM and KNMI/RACMOS), particularly in the south. But they overestimate solar radiation in the north.

For ET_o, most of correlation coefficients, at country scale, are between 0.6 and 0.75 (Figure 6~~Figure 6~~). Again, two models show better results: DMI/HIRHAM and KNMI/RACMO. With available climate parameters in these RCMs, we are able to better reproduce ET_o calculated with observed data. Errors for ET_o are low, between 0.7 and 1.7 mm/day, but standard deviation for models are above reference standard deviation (0.9 mm/day,). It denotes a higher time variability of values. Spatially, a south/north gradient exists in biases. In south, biases are positive, but low: ET_o calculated from RCMs tends to be underestimated. In north, biases are negative and higher: ETo in these stations is overestimated.

a)

b)

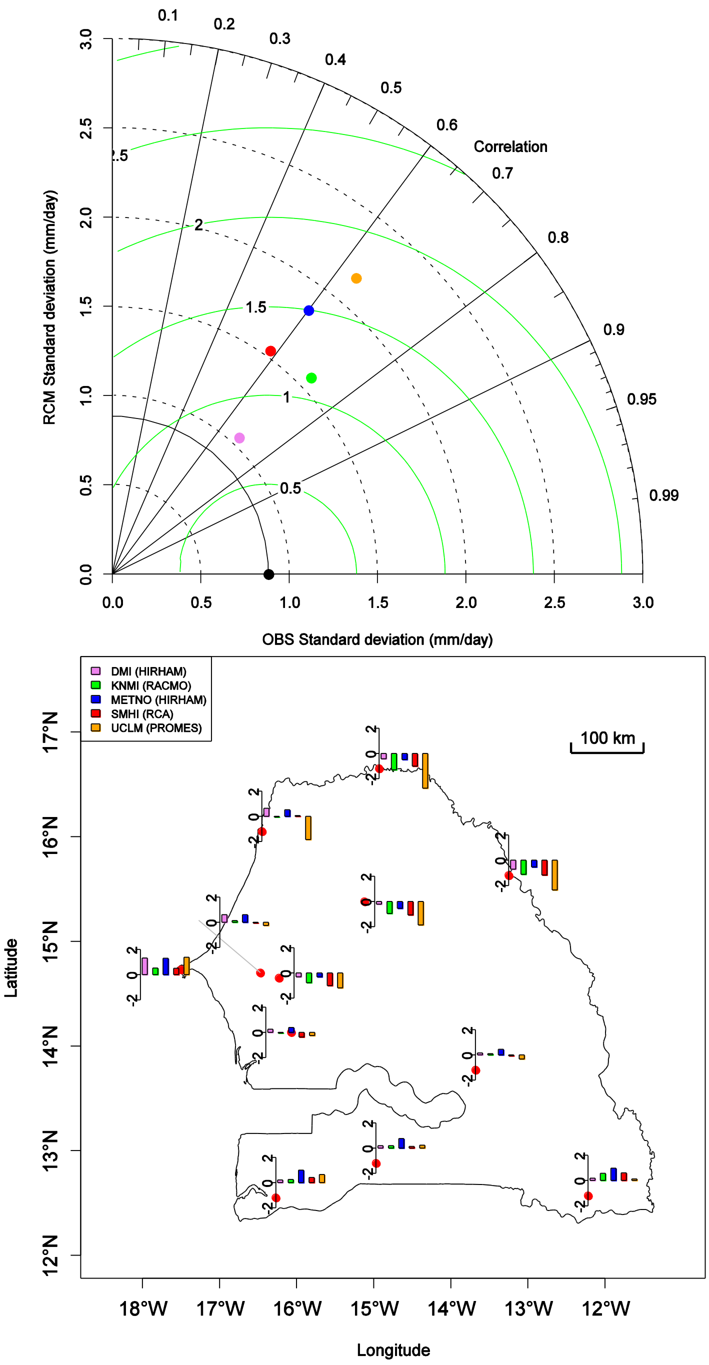


Figure 6: (a) Taylor diagram, comparing RCMs output (colors) and observations (black) for ET_o at country space-scale, from 15th April to 30th November, during 1990-2000, (b) biases calculated for ET_O for the same period for each model

Crop yields simulations for 2 sorghum varieties (Dingkuhn et al., 2008; ~~-~~Kouressy et al., 2008a and part 2.3) and for each station are carried out, with climatic parameters from observations and RCMs.~~.~~ Figure 7~~Figure 7~~ shows means (calculated from 12 stations) for observations and each RCM output, at country space-scale.

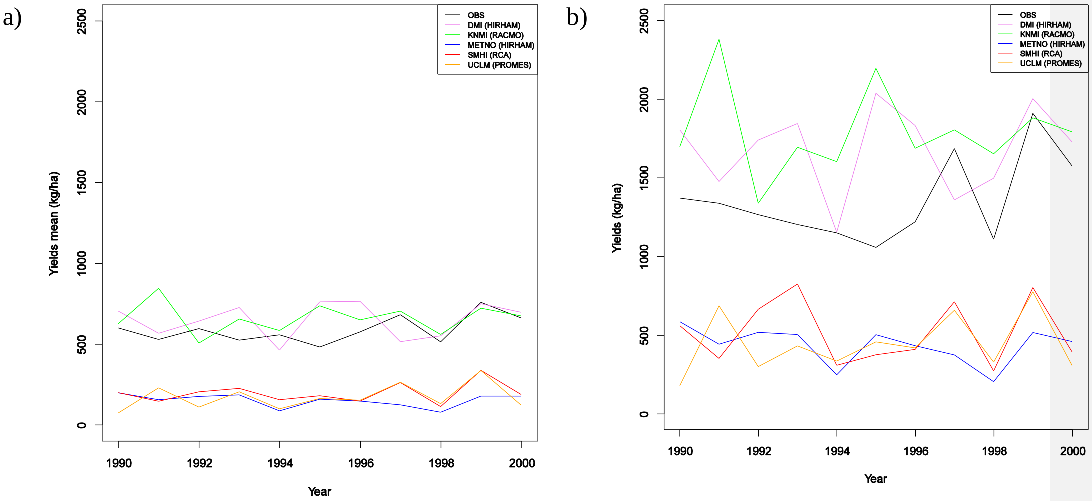


Figure 7: Spatial means for simulated crop yields from observations and RCMs output for (a) "local" and (b) "improved" sorghum varieties.

In term of potential yield, simulations with two models (DMI violet and KNMI green lines) are in the same range than simulations driven by observations (black line), for both varieties: *local* (Figure 7~~Figure 7~~a) and *improved* (Figure 7~~Figure 7~~b). For *local* variety, yields are about 600-700 kg/ha, according to results shown in previous studies (Kouressy et al., 2008b; Mishra et al., 2008). Simulations driven by both models present a good interannual variabililty, but have low correlation coefficients with simulations driven by observations: 0.09 for DMI and 0.07 for KNMI. For the other models, simulated yields means are below, about 200 kg/ha. But interannual variability is better reproduced for two models (SMHI and UCLM). Correlation coefficients respectively are 0.78 and 0.49. For METNO model, coefficient is lower (0.26). For *improved*, yields are about 1700kg/ha for observations, DMI and KNMI models, 500 kg/ha for the others model. With this variety, we have similar results: low correlations for DMI and KNMI (0.12 and 0.08, respectively), relative high correlations for SMHI and UCLM (0.55 and 0.57), and intermediate correlation for METNO (0.29).

Despite weak reproduction of some climatic parameters, generated ET_0 is good, mainly for two models, used by DMI and KNMI institutions. These two models show good potential yields, close to observations. In next section, these models will be used to evaluate future trends in crop yields, according to IPCC A1B climate change scenario.

3.2 Future trends for climate change

For the period 1990-2050, RCMs are driven by ECHAM5-r3 GCM output, run in a climate change context. The emission scenario chosen is a balance across all sources (A1B), which correspond to present-day conditions.

For the same period, crop yields driven by RCMs output are carried out for each station and crop. The purpose is (ii) to estimate expected trends in potential crop yields, at country space-scale, between the sub-periods 1990-2010 and 2030-2050; (ii) to see if geographical differences in trends exist.

First, means are calculated for each year, with all stations. Each value is normalized, to obtain relative values to the mean. Figure 8~~Figure 8~~ shows negative trends in yields for both RCMs. For DMI model (left panel), crop yields between 1990 and 2010 are 10% above average. But with time, yields amount decreases, and for the period 2030-2050, they are 15% below average. From the period 1990-2010 to 2030-2050, the decrease is about 10%. Precipitations show negative trend (blue line), with a decrease of 13% in seasonal rainfall (mid-April to late November), from the period 1990-2010 to 2030-2050, and for whole country. It seems that for the period 1990-2020, rainfall present not real trend, to stay at the level of 1970's rainfall (Nicholson, 2000). But after this period, a decreasing trend appear, maybe to the level of the late 1960's (Mahé and Paturel, 2009). Coefficients correlation between spatial means and precipitation are high: 0.91 for *local* and 0.90 for *improved*. It shows that **at region scale** crop yields amount are driven by rainfall amount. But these relations are partly due to the fact that there are spatial means: it rains more in south than in north of country, and there are more crop yields in middle and south than in north.

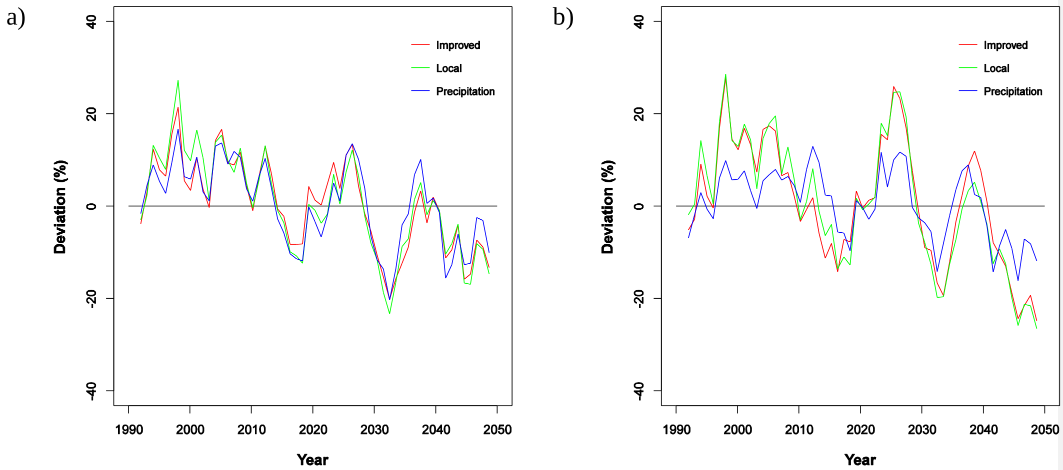


Figure 8: Time evolution in expected yields for "local" (green line) and "improved" varieties (red line), and in precipitation (blue line) for the period 1990-2050. Results are shown for (a) DMI and (b) KNMI models.

For KNMI model (right panel), crop yields between 1990 and 2010 are 10% or 15% above average. But for the period 2030-2050, they are 15% below average, and even 20% at the end of period. Between 1990-2010 and 2030-2050, the decrease is about 18%. Coefficients correlation between spatial means and precipitation are less important, but still high: 0.81 for *local* variety and 0.75 for *improved*. It shows that **at regional scale** crop yields amount are driven by rainfall amount. Between both sub-periods, the decrease for precipitation is about 11%, with same comment than for DMI. Both models show negative trend in crop yields, but they show differences in time variability. Yield forecast are more variable with KNMI model than with DMI model.

Decreasing in yields is not equally distributed in space. We calculated deviation between multi-model yields means, calculated for two periods: 1990-2010 and 2030-2050, for each station and for each sorghum variety. Results are shown in Figure 9~~Figure 9~~, for the *local* sorghum variety. Same trends exist for the *improved* sorghum variety.

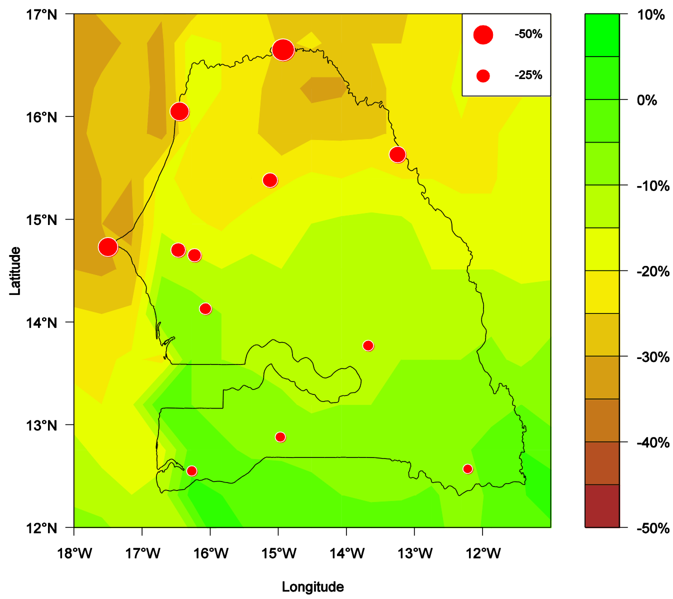


Figure 9: Multi-model yields ratio between 1990-2010 and 2030-2050, in percent for the *local* sorghum varieties.

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All stations show an expected negative trend, with values below average (red disk). But a strong south/north gradient appears in these values. In south, the expected decrease is only 10% below average. But in the central part of country, where majority of cultures are located, expected decrease in crop yields is between 15 and 30%. And in the north, the expected decrease is above than 50%. There are strong relationships between yields decreasing and rainfall decreasing, in agreement with rainfall forcing in crop model. In the central part of the country, decrease in yields is associated with a decrease in precipitation. Expected rainfall amount are between 5 and 35% below 1990-2010 mean.

We have to put these results into perspective, because sorghum varieties used here and farmer practices (optimum localisation, fertilization,…) are not those of country and also farmers use different varieties from north to the south cope with the climat. In this prospective study, expected trends in potential yields are negative. We presented potential yields simulations for 12 stations, but the north is mainly pastoral. So, firstly expected trend in these stations have less impact on cereal’s production at country scale, but show that rainfall in this region will decrease, with a potential strong impact on livestock feeding, secondly as we use only one variety over all the country there is probably variety more adapted to the driest zone. Another limitation of this study is than only one of the two available GCMs is used in this study. A part of trends in crop yields are due to GCM uncertainties, regionally downscaled by RCMs. ECHAM5 model is relatively wetter than HadCM3 (Thornton et al., 2010)and results shown could be the most optimistic for future.

4. Conclusion

With RT3, ENSEMBLES project provides regionalized climatic parameters for the AMMA-region. First analyses show that some climatic parameters are well reproduced by RCMs, as temperature or relative humidity. But some other parameters are reproduced with difficulty, precipitation or downward solar radiation for example. But when a new climatic parameter, depending on relative humidity, temperatures, solar radiation, sunshine duration and wind speed, is calculated on observations and RCMs output, results are pretty good. Potential yields simulation in present-day show a good ability of two models for reproducing amount in simulated yields driven by observations, But in term of temporal variability, these two models have some difficulties to well reproduce interannual variability. At the opposite, two models well reproduce interannula variability, but are not able to reproduce amounts. It will be interesting to explore why any model are able to well reproduce amounts **and** variability.

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We must underline that these results are obtained with varieties adapted in the center of Mali cope to the climate in this area and that farmers used different *local* varieties cope to the climat variation from the North to the South part of the country. We studied the ability of these varieties to obtain good crop yield. In present-day period, *local* variety is able to produce well amounts. But at country scale, we have to put the results into perspective, because of inadequacy of crops with the study area.

With RT2B, we have the same climatic parameters, calculated for the SRES A1B. First results show decrease in crop yields, at country scale (about 16%). And a gradient south/north appears in the decrease, with yields between 5 and 25% below 1990-2010 mean. It’s interesting to note that this trend is similar to this observed from the period 1950-1969 to 1970-1989. A possible outlook is to compare observed trends and impacts between these two periods and long range forecasts.

Next work is to use other RCMs output, driven by HadCM3 GCM, to improve knowledge of effects of climate change on yields in Senegal. But biases exist in data used, due to large-scale information basically interpolated at local-scale. In order to use GCMs output, a prior step is to correct biases with a statistical method (CDF-transform), developed to generate local cumulative distribution functions (CDFs) of surface climate variables from large-scale fields (Michelangeli et al., 2009). In order to test these corrections, we could carry out correlations between potential simulated crop yields and different climate variables (temperatures, solar radiation, ETo…) at different time scale (day, 10-day, month…). We could test effect of aggregation on crop yields.

In order to increase the number of stations used for crop yields simulations, an alternate analysis is possible, only using precipitation at station scale. Others climate parameters will be extrapolated from nearest stations, the spatial variability being more important for precipitation than for the others parameters.

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